Test Results of ITER Conductors in the SULTAN Facility

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Abstract. Starting March 2007, over 60 ITER cable-in-conduit conductors (CICC) have been tested in the SULTAN test facility in Villigen, Switzerland, including TF, CS, PF, CC and busbar samples. The test reproduces the actual operating conditions in the ITER coils, except for the hoop load and the CS peak field. Depending on the stage of the procurement, the SULTAN samples are categorized into Design Verification, Supplier Qualification (Phase I), Process Qualification (Phase II), Pre-Production and Series Production. The number of remaining samples to be tested during the ITER construction phase is about 40. For the NbTi CICC, the results confirm the prediction from the strand data, which are made taking the peak field over the conductor cross section as operating field. At low current density, where the n-index of the transition is measurable, the NbTi CICC and the NbTi strand have the same n-index. All the NbTi samples passed the supplier qualification phase. For the Nb_3Sn CICC, the performance prediction is not straightforward because of the irreversible degradation caused by filament damage occurring during cyclic loading. At the first run of the test campaign, the performance of all the Nb_3Sn samples largely meets the requirement for all the tested samples. Contrary to the NbTi CICC case, the n-index of the transition is substantially lower than in the strands, providing evidence of irreversible degradation. The performance loss upon load cycles and thermal cycles has a broad range among the various conductor samples. For the CS conductors, the final phase of the supplier qualification starts in November 2012.

1. Introduction

The SULTAN test facility at Villigen started as a Swiss-Italian-Dutch project in the late seventies with support of the European Commission [1]. The Swiss partner completed the facility in the nineties modifying the original magnet system of co-axial solenoids into a split coil system [2] with a 100 kA current source (flux pump) [3] and various minor upgrades [4]. Since 1994, the SULTAN facility is operated by the CRPP-EPFL (Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne).

In the ITER-EDA phase, half dozen of TF and CS conductors for the model coils were tested in SULTAN between 1998 and 2001 [5, 6]. The test of the actual ITER conductors started in 2007. Up to now, 29 TF conductor samples, 4 CS conductor samples and 6 NbTi conductor samples for PF, correction coils and busbar have been tested in SULTAN. The preparation and test of the samples run initially under bilateral contract between CRPP and the Domestic Agencies (DA). Starting May 2012, a framework contract coordinated by the ITER Organization (IO) covers all the CRPP activities. Within the three years duration of the contract, 129 weeks of SULTAN testing are foreseen, as well as the preparation of 34 Nb_3Sn CICC samples. The samples made of NbTi conductor are pre-assembled at the DA. As of October 2012, the Design Verification (DV) and Supplier Qualification (SQ) phases of the conductor procurement are completed for all conductors except CS. The Process Qualification (PQ) and Pre-Production (PP) tests are in progress for TF conductor.

2. The short Length Conductor Samples for SULTAN

The layout of the short length conductor samples is dictated by the test facility [4], with two straight, 3.6 m long conductor sections in a hairpin configuration, inserted in the gap of the split solenoid, with up to 11 T DC background field. In the 450 mm long high field zone, the conductor experiences the relevant transverse load. Cyclic load is achieved by sweeping up and down the operating current in constant background field – one TF load cycle lasts about 40 s. One thermal cycle requires to warm-up and cool-down the whole sample assembly and lasts about four days. The sample preparation procedure and instrumentation are described in [7-9]. An assembled TF conductor sample and the test geometry are shown in FIG. 1.

The main test for the ITER conductor samples is the current sharing temperature, T_{cs}, where field and current are constant and the temperature is increased till a stable transition is observed. The T_{cs} test is used to monitor the performance over load and thermal cycles. For the CS conductors, the measured performance must be scaled to 13 T and the hoop load must be also be accounted for. The test program is complemented by AC loss test before and after cyclic loading and other DC tests at various combination of field and current. A detailed description of the test programs for each conductor type is given in [9].

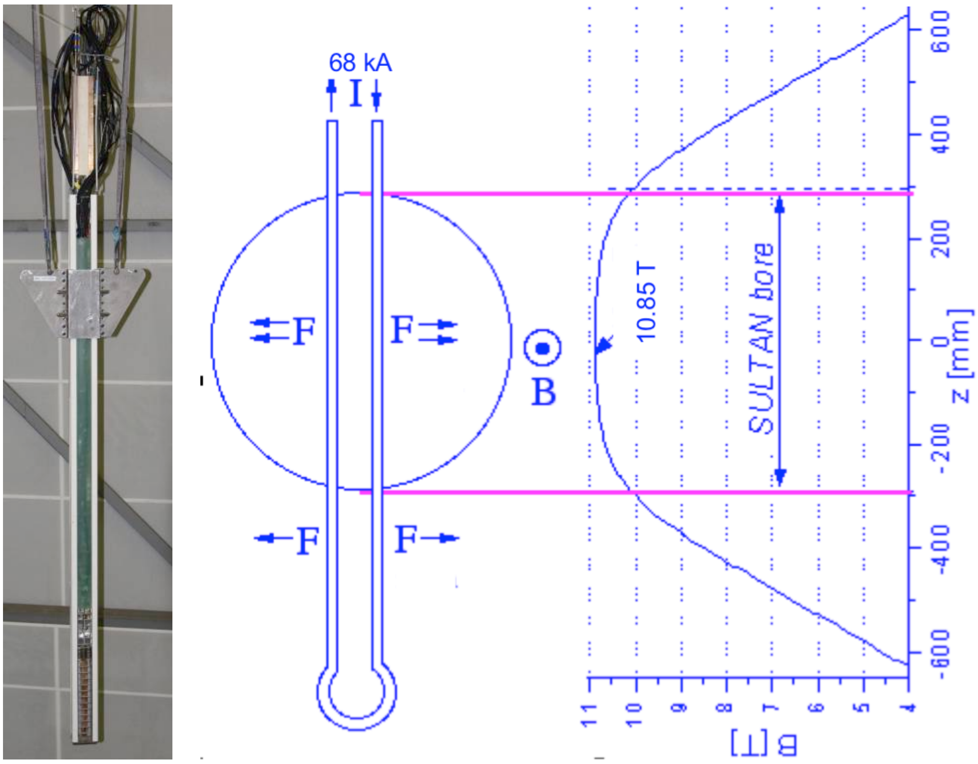

FIG. 1. An assembled TF conductor sample and the test geometry in SULTAN.

2.1. Validation of SULTAN Samples Results

The procedures and results of the SULTAN tests are continuously scrutinized by the SULTAN Working Group (CRPP, IO and DAs). Whenever a potential issue is identified, actions are undertaken to solve and fully validate the results.

The current distribution among the non-insulated elements of a superconductor (e.g. filaments in a strand or strands in a cable) is driven by the inductive voltage in pulsed mode and by the termination resistance distribution in DC mode. As the contact resistance of each current carrying element in the electrical termination cannot be identical, the non-homogeneous current distribution in superconductors is an intrinsic feature, which does not impair the performance, provided that current re-distribution is effectively driven by current sharing voltage when the conductor approaches the transition [10]. Indeed, dedicated investigation of the resistance distribution in termination of SULTAN samples [11-13] proved that the current re-distribution at the sample termination is effectively driven by extremely low voltage, without an impact on the n-index of the CICC. The solder filling procedure for the termination, introduced in 2008 [8] provides low, reproducible values for termination resistance.

Discrepancies between the n-index for the single strand and the cabled conductor at the same operating current density are observed for Nb_3Sn CICC but not in NbTi CICC, see FIG. 2. This feature is likely correlated with filament breakages [14] and hence local current sharing.

Early voltages observed well before the transition in the early samples in 2007, due to non-equipotential conductor cross section, triggered the use of arrays of six voltage taps over the conduit perimeter to assess the average voltage drop along the conductor and mitigate the baseline distortion. Arrays of four temperature sensors at each location, with resolution better than 5 mK, allowed to carry out calorimetric assessment of the transition, by measuring the temperature increase over the high field zone at constant mass flow rate - for TF conductor the T_{cs} power threshold in SULTAN is 306 mW. The comparison of electric and calorimetric measurements [7] provided the basis for the post-processing procedure, "straightening of the baseline", whenever the baseline deviates substantially from zero [9].

To preserve the thermal strain in the Nb_3Sn, induced by the differential shrinkage of the steel conduit and the Nb_3Sn strand from the 650°C to 4K, crimping rings are applied prior to the heat treatment to strongly engage cable and jacket and prevent slippage [9]. Upon cool-down, the TF conduit is in axial tension and the cable in axial compression. During the test of TF conductors in SULTAN, it is observed that the tensile strain on the jacket relaxes at the high field region but is maintained constant at the low field region [15-16], as the strong transverse

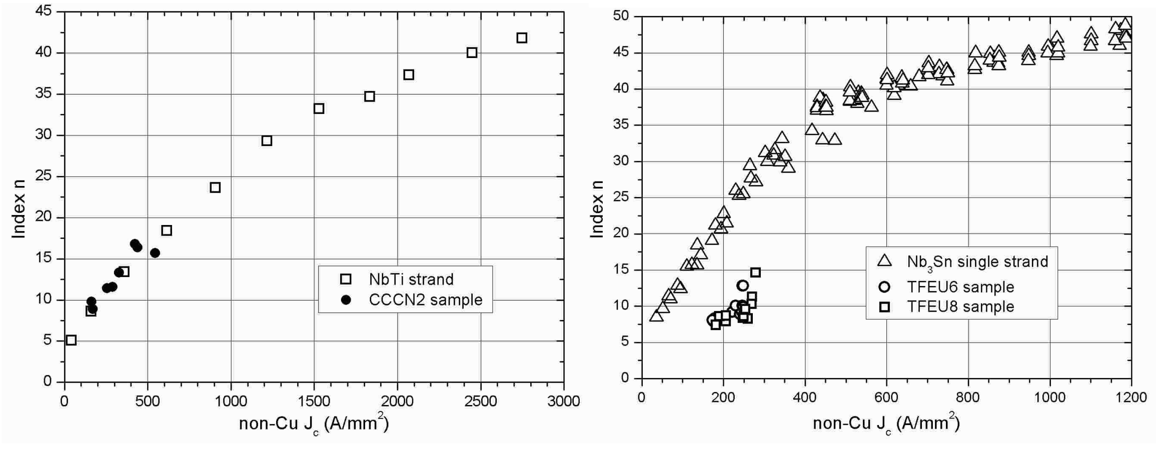

FIG. 2. Comparison of n-index for strand and CICC: NbTi (left) and Nb_3Sn (right).

load on the cable mechanically disengages the cable/jacket, likely causes strand degradation and weakens the cable modulus. The resulting enhancement of the compressive strain of the cable in high field is small compared to the reduced thermal strain in the SULTAN samples due to the lack of the bonded TF radial plates at cool-down [17].

The engagement of conduit and cable at the edges of the high field zone is crucial to prevent strain concentration in the cable; if the "disengaged" section would extend beyond the high field zone, the weakened cable at high field would get extra compression. To solve this issue, a dedicated test was carried out comparing the performance of two identical conductor sections, one of which had additional crimping rings at the edge of the high field zone to prevent any stress concentration from the edge zone. The performance result was identical for both sections, proving that the "non-homogeneous strain relaxation" is strictly local [16].

3. Results of NbTi CICC

As of September 2012, six NbTi samples corresponding to the six layouts of ITER NbTi CICC have been tested as Phase I, i.e. Supplier Qualification Samples. Table I summarizes the identity of the six NbTi samples, the performance results at the reference background field and operating current and the required performance. The DC characterization extends over a range of operating field and current. Up to 2000 load cycles are applied. As in former tests on NbTi CICC, the T_{cs} performance is not affected by load cycles but the AC loss decreases upon cyclic loading due to the enhanced transverse resistance at the strand crossovers.

3.1 The Self-field induced Sudden Take-off

For a decade sudden take-off, i.e. superconducting transition without current sharing, has been observed in NbTi CICC operating at high current. Such reproducible behavior is not linked to transient disturbances and instability [18]: the large gradient of self-field over the conductor cross section causes high, localized electric field, which drives a quench before the measured, longitudinal average electric field achieves the criterion of 10 μV/m. At increasing operating current (self-field), the take-off electric field becomes eventually not detectable.

Figure 3 shows the take-off electric field vs. operating current for the ITER NbTi conductors (exponential lines) and the operating current at the reference point (vertical lines): for the Main Busbar, PF5 and PF2/3/4 conductors, the take-off at the reference point is lower than 10 μV/m and the T_{cs} performance is replaced in Table I by the take-off performance, T_q. For the smallest CICC, the Correction Coil conductor, with the lowest operating current and self-field, the sudden take-off is not an issue at all.

As long as the current re-distribution can take place at low voltage, T_q is close to the T_{cs} predicted from the strand performance, assuming the peak field as operating field [19]. In a few cases, the measured T_{cs} performance is slightly better than the predicted one at the peak field: this means that the operating conditions (self field gradient) and the conductor layout

TABLE I: SUMMARY OF NbTi CICC SAMPLES TESTED IN SULTAN

Sample	DA	Conductor type	Test date	Reference Point	Measured/Specified T_{cs}
PFCN1	CN	PF2/PF3/PF4	May 2010	4.2 T – 50.0 kA	6.33 K / 6.1 K
PFEU1	RF	PF1/PF6	September 2010	5.65 T – 48.0 kA	6.02 K / 5.9 K
PFCN2	CN	PF5	March 2011	4.86 T – 52.0 kA	6.15 K / 6.1 K
MBCN1	CN	Main Busbar	July 2011	3.22 T – 45.5 kA	6.95 K / 6.7 K
CCCN2	CN	Correction Coil	August 2011	3.83 T – 10 kA	7.10 K / 7.0 K
CBCN1	CN	CC Busbar	August 2012	2.63 T – 10 kA	7.51 K / 7.0 K

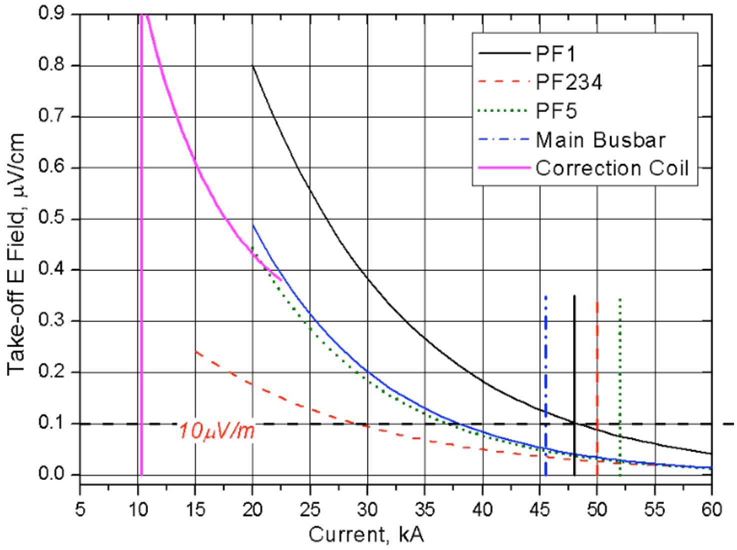

FIG. 3. Take-off voltage vs current for the NbTi ITER CICC.

(twist pitches, transverse resistance, n-index, cu:non-cu ratio) allow an enhanced current sharing, reducing the "effective" field to below the value of the peak field. The sudden take-off is not observed in Nb_3Sn based CICC, where the lower sensitivity to the self-field gradient is due to the lower $\partial J_c/\partial B$ and to the lower n-index of transition. In fact, the effective field for Nb_3Sn CICC is much closer to the average field than to the peak field.

4. Results of TF Conductors

The test of ITER TF conductors started in March 2007 with a number of Design Verification (DV) samples. The observed performance degradation with cyclic loading led to minor layout variations. The comparison of two pitch sequences and two void fractions, suggested in [20], led to the definition of the "Option II" TF cable (long pitch sequence and 29% void fraction), which was recommended in the Qualification Samples (QS) starting in 2009 [21].

A summary of the T_{cs} results of TF samples by voltmetric method is gathered in Table II, except those where both sections are DV. The required T_{cs} at 68 kA and 10.78 T background field is $T_{cs} \geq 5.7$ K ± 0.1 K after 1000 load cycles (no thermal cycle). The performance reported in Table II is at the start and end of the whole campaign, including the thermal cycle(s) and a non-identical number of load cycles (discrepancies up to 50 mK compared to other sources may be due to data processing differences). The results are not identical for the two conductors legs of the same sample: in fact, in most samples the two conductors differ either because of strand supplier or layout, heat treatment, production batch. Even in nominally identical conductors, performance differences, up to 0.3 K are observed along the test, mostly decreasing after the cyclic loading [22].

The performance loss upon load/thermal cycles varies substantially from sample to sample, from less than 0.1 K to over 0.5 K, even when the cable parameters (twist pitch and void fraction) are identical. The sensitivity of the Nb_3Sn strands from various suppliers to the combined axial and transverse loads on the strand bundle is the key to understand the different irreversible degradation. The degradation rate is not constant, with higher rate observed in the first 200 load cycles. Consecutive thermal cycles do not affect the performance, opposite to thermal cycles alternated with load cycles [23].

TABLE II: SUMMARY OF TF CONDUCTOR SAMPLES TESTED IN SULTAN

Sample name	Sample type	Test date	Initial T_{cs}, K	Load/thermal cycles	Final T_{cs}, K
TFEU3	SQ / SQ	March 2009	6.09 / 7.05*	1100 / 1	5.68 / 6.68
TFEU4	SQ / SQ	April 2009	7.16 / 6.90	1125 / 1	6.57 / 6.55
TFEU5	SQ / SQ	September 2009	6.61* / 6.35*	1125 / 1	6.24 / 5.98
TFEU6	SQ/ SQ	March 2012	6.26 /6.26	1140 / 1	5.75 / 5.74
TFEU7	PQ / PQ	September 2012	7.49 / 6.42	1000 / 1	6.67 / 5.89
TFEU8	PQ / PQ	August 2012	6.13 / 6.27	1000 / 1	5.66 / 5.67
TFUS1	DV / SQ	March 2008	6.71 / 6.38	1200 / 0	6.69 / 6.24
TFUS2	SQ / DV	May 2008	7.23 / 5.71	915 / 1	6.44 / 5.61
TFUS4	SQ / SQ	May 2009	7.13 / 7.12	600 / 0	6.82 / 6.98
TFJA4	SQ / SQ	November 2009	6.48 / 6.28	1000 / 1	6.16 / 5.98
TFJA5	PQ / PQ	January 2011	6.22 / 6.33	7500 / 4	5.03 / 4.95
TFJA6	PP / PP	April 2011	6.19 / 6.04	1000 / 1	5.56 / 5.35
TFCN1	SQ / SQ	June 2009	7.29 / 7.23	1100 / 1	6.86 / 6.89
TFCN2	SQ / SQ	October 2010	6.67 / 7.03	1200 / 1	6.43 / 6.44
TFCN3	SQ / SQ	November 2010	6.42 / 6.24	1000 / 1	6.08 / 5.93
TFCN4	PQ / PQ	August 2012	6.55 / 6.58	1000 / 1	6.35 / 6.27
TFKO2	SQ / SQ	October 2008	6.58 / 6.31	1000 / 1	6.37 / 5.96
TFKO3	SQ / SQ	August 2010	6.83 / 7.22	1000 / 1	6.62 / 6.90
TFKO4	PQ / PP	June 2012	6.96 / 6.89	1000 / 1	6.62 / 6.60
TFRF2	SQ / SQ	November 2008	6.44 / 6.44	707 / 1	6.31 / 6.26
TFRF3	PQ / PQ	May 2012	6.15* / n.a.	1000 /1	6.06 / n.a.

* second run

The actual mechanism of degradation/breakage upon combined load and thermal cycles is not satisfactorily modeled so far. Minor performance improvement has also been observed in few cases, both upon cyclic loading and thermal cycles, mostly within 0.1 K. Obviously, such improvements are correlated with reversible mechanisms, e.g. strain relaxation. Only in one case (CSIO2 – short twist) the final performance is better than the initial one.

The results of the initial T_{cs} do not match the prediction from the strand scaling law when realistic values of the axial strain, ε, are assumed. An artificial, “effective” value of the axial strain must be introduced to fit the strand data and the CICC results [24], suggesting that, as in the CS Model Coil one decade ago, irreversible degradation starts at the first charge.

5. Results of CS Conductors

Four CS conductor samples have been tested since 2010, the first one assembled in Japan. In the first two samples, CSJA1 and CSJA2, vacuum leaks developed in the JK2LB conduit after assembly. The test program, number of campaigns and load/thermal cycles were not identical. The T_{cs} test is carried out at 10.85 T / 45.1 kA. The cyclic loading is at 48.8 kA / 10.85 T. In the ITER CS, with over 50 000 load cycles, the actual field is about 1.5 T larger and the hoop load mitigates the thermal strain. The results are gathered in Table III.

Compared to the TF tests, a much larger number of cycles was applied, up to 17 000 for CSJA2. The degradation rate was very high in CSJA1, where an initial performance improvement was likely due to slippage (strain relaxation) at the termination. In CSJA2 the initial performance was extraordinary high, due to an excellent strand, but the degradation rate was similar to most TF conductors, with no clear sign of saturation. With CSIO1, the original cable layout [25] with 2 Nb_3Sn strands (cu:non-cu = 1) and one copper wire in the first triplet was compared with a triplet where 3 Nb_3Sn strands are used with cu:non-cu = 1.5

TABLE III: SUMMARY OF FOUR SAMPLES OF CS CONDUCTOR TESTED IN SULTAN

Sample	Start test date	Cable layout	Initial T_{cs}, K	Load/thermal cycles	Final T_{cs}, K
CSJA1	October 2010	DDD 2009	5.94 / 6.04	6000 / 1	4.66 / 5.05
CSJA2	June 2011	DDD 2009	7.16 / 6.78	17050 / 4	6.20 / 5.44
CSIO1	January 2012	3sc / 2sc+1cu	7.32 / 6.67	11280 / 2	6.99 / 6.25
CSIO2	March 2012	Short / Long pitch	6.95 6.99	6150 / 2	7.14 / 6.70

(as in the ITER CS Model coil). Beside the obvious advantage from the 20% larger non-cu cross section, the degradation rate was similar for the two versions, ruling out a lesser sensitivity to transverse load of the 3 vs. (2+1) layout. In CSIO2 a very short cable pitch sequence was compared with a long, “optimized” one, with the results of a very stable performance (no cyclic load degradation and even a small improvement) for the very short pitch, as predicted in [26]. One new SQ sample of CS conductor, CSJA3, with short pitches will be tested in the end of 2012.

6. Conclusion

The SULTAN test facility has a long and reliable history in testing conductors for the fusion program. Recently it has found intensive use as the only available test and qualification facility for NbTi and Nb_3Sn conductors for ITER. The large conductor size needed improvements in the sample design and instrumentation. An intensive program of validation has shown that the conductor samples reflect most aspects of the conductor behaviour in a coil, except the operating strains. In particular they are able to indicate sensitivity of some Nb_3Sn strand types to filament fracture under CICC magnetic loads, and are able to indicate improved CICC cable configurations to mitigate this fracture. The samples have successfully qualified NbTi conductors for the PF, CC and busbars, 6 Nb_3Sn strand-cable combinations for the TF coils and 2 Nb_3Sn strand-cables for the CS coils. Questions have been raised over 2 TF coil strand types and one strand type proposed for the CS, for which further tests are underway, with back-up options available if the strands are unsuitable.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

[1] ELEN, J.D., et al., “The Superconductor Test Facility SULTAN” IEEE Mag **17**, (1981) 490.

[2] BALSAMO, E.P., et al., “Final Tests of the SULTAN 12 T Facility in the split Coil Configuration”, Fusion Technology 1992, 768.

[3] PASZTOR, G, et al., “Design, Fabrication and Testing of a 100 kA superconducting Transformer for the SULTAN Test Facility”, Proc. of MT 15, 839, Beijing Oct. 1997, Science Press 1998.

[4] BRUZZONE, P., et al., “Upgrade of Operating Range for SULTAN Test Facility”, IEEE Appl Supercond **12**, (2002) 520.

[5] CIAZYNSKI, D., et al., “Test Results and Analysis of two European full-size Conductor Samples for ITER”, IEEE Appl Supercond **10**, (2000) 520.

[6] BRUZZONE, P., et al., “Test Results for the high Field Conductor of the ITER Central Solenoid Model Coil”, Adv. Cryog. Eng., **45**, (2000) 729.

[7] BRUZZONE, P., et al., "Methods, Accuracy and Reliability of ITER Conductor Tests in SULTAN", IEEE Appl Supercond **19**, (2009) 1508.

[8] BRUZZONE, P., et al., "Status Report of the SULTAN Test Facility", IEEE Appl Supercond **20**, (2010) 455.

[9] ITER Organization, IDM Folder "Test Procedure"

[10] STEPANOV, B., "Impact of impressed current unbalance on n-index", IEEE Appl Supercond **14**, (2004) 1495.

[11] CAU, F., et al., "Interstrand Resistance and current redistribution in a Cable-In-Conduit Conductor (CICC) termination", IEEE Appl Supercond **19**, (2009) 1452.

[12] VAN LANEN, E.P.A., et al., "Interstrand Resistance Measurements on the Conductor Termination of TFPRO2 and JATF3 SULTAN Samples", IEEE Appl Supercond **20**, (2010) 474.

[13] CAU, F., et al., "Interstrand resistance and contact resistance redistribution on terminations of ITER short samples", IEEE Appl Supercond **20**, (2010) 478.

[14] SANABRIA, C., et al., "Evidence that filament fracture occurs in an ITER toroidal field conductor after cyclic Lorentz force loading in SULTAN", Supercond. Sci. Technol. **25**, (2012) 075007.

[15] BRUZZONE, P., et al., "Results of thermal strain and conductor elongation upon heat treatment for Nb_3Sn Cable-in-Conduit Conductors", IEEE Appl Supercond **20**, (2010) 478.

[16] MARCH, S., et al., "Results of the EUTF6 conductor sample tested in SULTAN" Presented at ASC Conference, Portland, October 2012.

[17] BRUZZONE, P., et al., "Operation and test results from the SULTAN test facility", IEEE Appl Supercond **22**, (2012) 9501704.

[18] WESCHE, R., et al., "Sudden take-off in large NbTi conductors: not a stability issues", Adv. Cryog. Eng. Mat. **50 B**, (2004) 820.

[19] PONG, I., et al., "Current sharing temperature of NbTi SULTAN samples compared to prediction using a single pinning mechanism parameterization for NbTi strand", Supercond. Sci. Technol. **25**, (2012) 054011.

[20] NIJHUIS, A., ILYIN, Y., "Transverse load optimization in Nb_3Sn CICC design; influence of cabling, void fraction and strand stiffness", Supercond. Sci. Technol. **19**, (2006) 945.

[21] DEVRED, A., et al., "Status of ITER conductor development and production", IEEE Appl Supercond **22**, (2012) 4804909.

[22] UGLIETTI, D., et al., "Statistical analysis of current-sharing temperature evolution in Nb_3Sn CICC for ITER", IEEE Appl Supercond **22**, (2012) 4802204.

[23] MARCH, S.A., et al., "Effect of thermal loading on Nb3Sn CICC performance", IEEE Appl Supercond **22**, (2012) 4803604.

[24] BRESCHI, M., et al., "Evaluation of effective strain and n-value of ITER TF conductor samples", IEEE Appl Supercond **21**, (2011) 1969.

[25] ITER Organization, IDM Folder, DDD11-7_Conductors.

[26] MARTOVETSKY, N., "Test results of the first US ITER TF conductor in SULTAN", IEEE Appl Supercond **19**, (2009) 1478.